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Effect of Cup Length on Film Profiles in Gas-Centered Swirl-Coaxial Injectors

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Recent interest in LOX-hydrocarbon rocket engines has resulted in the need for design criteria and scaling laws for injectors which work well in such an environment. One injector type that has been shown to work well in LOX-hydrocarbon engines is a Gas-Centered Swirl-Coaxial (GCSC) Injector. While earlier work has focused on a number of the important parameters, one that has been left unexplored is the injector cup length. In this study the effect of the injector cup length on the atomizing film in GCSC injectors is explored. The length of the atomizing film is used as reference parameter for the overall spray quality. Using laser-sheet illuminations along with water and nitrogen as the working fluid, film lengths were determined in six unique injector geometries and over a number of flow conditions. Each injector geometry and flow condition was tested with two injector cup lengths. Results will show that the injector cup length has little effect on the films for test conditions with momentum-flux ratios greater than 400 as long as the film is completely broken up within the cup.

Nomenclature

h	= film height
L_c	= injector cup length
L_f	= liquid film length
m	= mass flow rate
r_g	= initial injector gas post radius
r_o	= injector outlet radius
r_p	= injector gas post radius at end of sheltered lip
S	= injector step height at end of sheltered lip
X	= downstream coordinate
Y	= radial coordinate
Φ	= gas to liquid momentum-flux ratio
ρ	= density
τ	= initial liquid film thickness

Subscripts

g	= denotes a gas property
l	= denotes a liquid property
$nominal$	= refers to standard injector cup length (34.54 mm)
$short$	= refers to standard injector cup length (19.41 mm)

I. Introduction

In recent years the United States rocket community has explored switching from cryogenic hydrogen to hydrocarbons as the primary fuel for liquid rocket engines. A great deal of this interest has centered on the use of a staged combustion cycle with an oxygen rich preburner. In such a cycle the full flow of oxidizer is run through the preburner resulting in complete vaporization of the oxidizer before injection into the main combustion chamber. Given the oxidizer to fuel mixture ratios at which hydrocarbon rockets typically operate (~3-3.8 for LOX-RP1), a very energetic gas flow is available to atomize the liquid hydrocarbon fuel. One injector type that makes use of this

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high energy flow is the Gas-Centered Swirl-Coaxial (GCSC) injector.^{1,2} While this injector has been used in Russian rocket engines (example: RD-170),^{3,4} it has received less attention in the United States and the design criteria are unclear.

A schematic of a GCSC is shown in Fig. 1. In this configuration liquid fuel is injected through 4 tangential holes along the outer wall of the injector into a shrouded channel. The shrouded channel allows a swirling wall bonded film to form before being brought into contact with the energetic axial gas flow. What makes the GCSC injector unique is that atomization occurs inside of the injector cup where the liquid is still a wall bounded film. This is in contrast to the more common pressure swirler and airblast atomizers where atomization occurs outside of the injector and the liquid sheet or jet is completely bounded by gas.⁵ Studies of atomization from wall-bounded films are generally confined to oceanic flows or annular flows in cooling tubes; both of these systems operate at mass flows rates which are substantially lower than those required in rocket engines.⁶ As a result it is difficult or impossible to leverage the predictive tools used in other systems to develop design criteria for rocket engines. This difficulty was recognized early in the US development of GCSC injectors and models specific to GCSC injectors were sought.² Further understanding determined that these injectors operate in a mode where stripping due to aerodynamic forces and turbulent gas-phase structures are of primary importance.⁷ Utilizing these ideas earlier work demonstrated that the performance of a GCSC (measured by the uniformity of the spray and the length of the film in the cup) can largely be predicted by the use of the gas to liquid momentum-flux ratio (Φ) as the scaling parameter.⁸ However, this scaling parameter alone was not able to collapse average film lengths from all experimental geometries to a single curve or predict exactly when nonuniformities in the spray would occur.^{9,10} Geometric variations included in this previous work were the cup radius, step thickness, gas radius at end of sheltered lip, and initial film thickness. One important geometric parameter which was not investigated was the injector cup length (L_c).

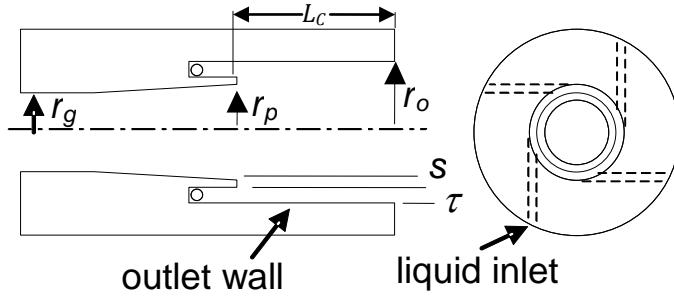


Figure 1. In this schematic of a gas-centered swirl-coaxial injector r_g represents the initial gas radius (always 6.35 mm), L_c the injector cup length (34.54 or 19.41 mm), r_p the gas post radius at the end of the sheltering lip, r_o the outlet radius, S the step height and τ the initial film thickness. Table 1 lists the values of these dimensions used in the experiments.

For a GCSC injector to function properly the liquid film must be completely atomized before the end of the injector cup. If the liquid film is not completely broken up within the cup then a secondary, hollow, outer cone will form. This cone contains many droplets which are at least an order of magnitude greater in diameter than the droplets in the primary, solid cone. For optimum performance this secondary cone must be avoided at all operating conditions. Given the throttleability requirements (~33%-133%) of modern liquid rocket engines the momentum-flux ratio and, therefore, the film length can change significantly over the course of a firing. Since the geometry is fixed for a given engine this results in a varying distance between the end of the film and the end of the cup making any effect of the injector cup length on the atomization quality of paramount importance. Simply setting a very large cup length to minimize this change is not the answer since this could result in combustion occurring inside of the injector greatly increasing heat transfer to the face plate and adding considerable engine weight. In addition it is common to vary the cup length across the face of the injector to act as acoustic dampers. For these reasons and because of the need for simple design criteria experimental data is needed to understand if and how cup length affects the atomization performance of GCSC injectors.

In this paper the effect of cup length on the film profiles, film length, and nonuniformities is explored in GCSC injectors. Measured film lengths and profiles are compared for twelve GCSC injectors (six different liquid post geometries with two injector cup lengths). The experimental geometries and methods are outlined below. A brief overview of observed nonuniformities from earlier studies and the choice of the momentum-flux ratio to scale film length (used as a metric for injector performance) are provided as a baseline for this work. Results will show that the

injector cup length has little effect on the films for test conditions with momentum-flux ratios greater than 400 as long as the film is completely atomized within the cup. The paper concludes by discussing the implications of these findings on the design of GCSC and planned future work.

II. Experimental Setup

As mentioned in the introduction, a gas-centered swirl-coaxial injector relies on energetic, fast-moving gas flow to produce droplets from a swirling, wall-bound film. There the film is created by introducing the liquid through holes drilled tangential to the injector cup. The unswirled gas enters down the centerline. The injector used in this study was designed to be modular. An acrylic outlet section is changeable to give an outlet radius of 7.620, 9.525 or 11.430 mm with an injector cup length of 34.544 mm. For the present study an additional acrylic outlet section was made with a 9.525 mm radius and an injector cup length of 19.406 mm. In this work the 34.544 mm injector cup length is referred to as the “nominal” length and the 19.406 mm cup length as “short”. An acrylic insert forms the last portion of the gas post and the initial shelter for the liquid; it is also interchangeable to allow gas post radii from 3.429 mm to 9.271 mm and initial film thicknesses of 1.321, 1.651 and 1.981 mm. Upstream of the acrylic section is a stainless steel section which forms ~180 mm of gas post with a fixed radius of 6.35 mm resulting in an inlet L/D ratio of ~14. The specific injector geometries are given in Table 1. Injector cup length was only tested on the “ON” (cup radius 9.525 mm) geometries. Since this is a cold flow study, water and gaseous nitrogen was used as a surrogate for a propellant combination of liquid hydrocarbon and gasified LOX.

Gas and liquid flow rates are controlled using calibrated sonic nozzles and cavitating venturis, respectively. The calibration and selected pressure transducers allow mass flow rates to be known to within 0.227 g/s (~0.25%). A valve downstream of the venturi (but upstream of the injector) insured that there was sufficient back pressure to minimize acoustic noise. All tests are performed with atmospheric back pressure. The gas flow rates were varied from 0.0187-0.0798 kg/s with clusters around 0.0227, 0.0350, 0.0454 and 0.0680 kg/s. The liquid flow rates were varied from 0.0236-0.0794 kg/s with similar clustering. The momentum-flux ratio, defined as $(\rho_l/\rho_g)(m_g/)^2\{\tau(2r_o - \tau)/[r_o - (\tau + s)/2]\}^2$, was varied between 40 and 1050.

During testing bubbles were observed in the tangential water inlet holes. At times these bubbles occupied a nontrivial portion of the liquid-channel volume. This problem was caused by dissolved gas coming out of solution due to the large pressure drop over the cavitating venturi. To eliminate the bubbles the water in the run tank was recirculated while placed under vacuum; this process was continued for 8-12 hours prior to testing. Additionally, a bubble trap was added downstream of the venturi to eliminate any remaining bubbles. After the implementation of this system, no downstream bubbles were observed. Despite the great pain taken to eliminate this variable, subsequent analysis showed it to have little effect on the atomization behavior.

Liquid film profiles were imaged using a two-laser lighting method. Two green, 500 mW, adjustable-power DPSS lasers were placed on opposite sides of the test section. An identical combination of a cylindrical concave and a spherical convex lens were used with each laser to form a two inch high laser sheet. After aligning the two sheets on top of each other the acrylic injector body was placed in the middle of the two-laser setup. The sheets were placed 0.5 to 1 mm forward of the injector midline to maximize light scattering to the camera. A schematic of the setup is shown in Fig. 2. A Vision Research Phantom v7.3 camera positioned 90° from the sheets was used to capture the video at 6006 fps. The exposure time was 150

Name	r_o (mm)	τ (mm)	r_g (mm)	s (mm)
ODHUTD	7.620	1.321	3.429	2.870
ODPDTD	7.620	1.321	5.461	0.838
ODHNTN	7.620	1.651	4.445	1.524
ODPDTN	7.620	1.651	5.461	0.508
ODHUTU	7.620	1.981	3.429	2.210
ODHDTU	7.620	1.981	5.461	0.178
ONPDTD	9.525	1.321	5.461	2.743
ONHNTD	9.525	1.321	6.350	1.854
ONPDTN	9.525	1.651	5.461	2.413
ONPNTN	9.525	1.651	6.350	1.524
ONPUTN	9.525	1.651	7.468	0.406
ONPNTU	9.525	1.981	6.350	1.194
OUHUTD	11.43	1.321	7.239	2.870
OUHDTD	11.43	1.321	9.271	0.838
OUPNTN	11.43	1.651	6.350	3.429
OUPUTN	11.43	1.651	8.407	1.372
OUHUTU	11.43	1.981	7.239	2.210
OUPUTU	11.43	1.981	8.407	1.041
OUHDTU	11.43	1.981	9.271	0.178

Table 1. The insert names and their attendant geometries are given above. The naming convention is to list the relative size of the (O)utlet and (P)ost radii and the film (T)hickness as either (D)own or (U)p from (N)ominal. In some inserts the (H)eight of the step plus film thickness is referenced instead of the gas post

microseconds. The power of each laser was adjusted independently to achieve equal lighting and adequate intensity of both the top and bottom film. Assessment of each setting was performed by eye.

Image processing was done via Matlab routines to obtain average and instantaneous film profiles. Once the 14-bit image was converted to an array, vertical slices of the picture were examined. Each vertical slice was further divided into two areas where the film interface was likely to occur (since the film is visible on both sides of the injector). These windows were based on the known edge of the injector body and the previous maximum location of the film (near the beginning, a maximum possible height based on the distance to the top of the sheltering lip was used). Within these windows the largest increase in intensity was marked as containing the film boundary and the largest increase over a single pixel within this area was chosen as the actual boundary. Lighting variations due to the turbulent nature of the flow and the atomization process occasionally produce difficulties, so care must be

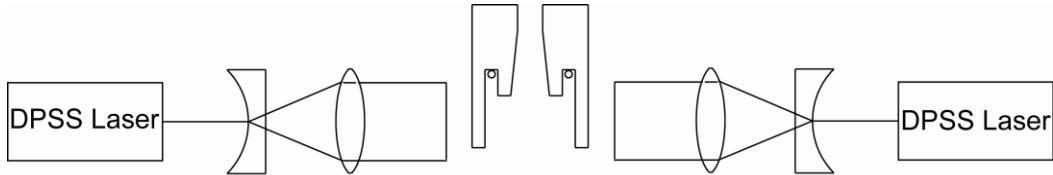


Figure 2. The two-laser experimental setup used to image the wall bounded film profiles. The laser sheets illuminated the test article from just upstream of the sheltered lip to a few mm below the end of the injector.

taken to ensure bright areas due to these variations are not mistakenly labeled as film boundaries. Final acceptance of the film profile was based on user viewing of the original movies with the found film profiles overlaid. In earlier work insufficient or nonuniform lighting resulted in a nontrivial percentage of movies being unusable.⁹ However, the two-laser setup used here largely eliminated these problems. Average film profiles and average lengths were obtained by averaging 5000 instantaneous instances (approximately 1000 more than analysis indicated was needed for the averages to fully converge). Due to the lighting changes and the ever-thinning nature of the film, it is difficult to estimate the accuracy with which the length is actually captured. Additionally, the film length is not steady. The accuracy expected, then, can be based on the standard deviation of the measured film length which is reported later.

III. Previous Work Overview

Earlier work on GCSC injectors using a general atomization model indicates that there are five nondimensional parameters which govern atomization momentum-flux ratio, Weber number, Reynolds number, and two pseudoFroude numbers.⁷ These nondimensional parameters account for aerodynamic, surface tension, viscous, gravity and centripetal forces respectively. In the context of rocket engines GCSC injectors operate in a regime where the aerodynamic forces are dominant, and, therefore, the momentum-flux ratio is the key parameter in determining atomization behavior.⁷ From the observation that aerodynamic forces are dominant and the nature of atomization from gas-phase turbulence it has been argued that the film length is directly related to the amount of atomization occurring, the droplet size and spray distribution.⁹ This argument is partially based on the idea that the shorter the film length the earlier the primary atomization occurs and, therefore, the earlier secondary atomization takes place producing even smaller droplets. Of course, earlier droplet production could lead to coalescence; however, the large gas velocities that produce these droplets produce high droplet Weber numbers, favoring breakup. From this information it is expected that the film length should be strongly related to the momentum-flux ratio and a good indicator of overall spray quality (droplet size and distribution).

When defining the momentum-flux ratio for a GCSC injector the question of the correct liquid and gas velocity arises. The geometric complexities of a GCSC injector make the use of a general scaling parameter difficult since variables included need to be easily calculable or measurable. After trying a number of logical scaling possibilities, earlier work found the best collapse of the available data using velocities based on the initial film thickness and the average gas-post radius from contact with the film to exit.⁹ Mathematically this resulted in the momentum-flux ratio being defined as $\Phi = (\rho_l/\rho_g)(m_g/m_l)^2\{\tau(2r_o - \tau)/[r_o - (\tau + s)/2]\}^2$. Note that this definition is based on the mass flow rates of the liquid and gas because they are the measured quantities. Also this definition uses only the axial portion of the liquid velocity ignoring the swirling of the liquid. The tangential portion of the liquid is difficult to measure and costly three-dimensional CFD simulations would be needed to accurately model it. Its effect on atomization/design remains for future work.

To illustrate the use of the momentum-flux ratio in scaling the average film length, the film length versus momentum-flux ratio is plotted in Fig. 3 for three different injector geometries. This film length is the average from both side of the injector cup. Why these two values sometimes differ is discussed in section IV. Figure 3 shows that the film length does correspond with momentum-flux ratio; however, the momentum-flux ratio is not able to fully collapse all geometries to a single curve but into families of curves.⁹ This collapse into a family of curves and not a single curve is not unexpected. Given the complexity of the flow it is conceivable that a single scaling is not possible over the wide range of geometries and operating conditions. Of course, this is substantially less powerful then having a single scaling. Two additional important points from Fig. 3 are that there is a limit on how short the film can become (which results in a greatly diminished effect of the momentum-flux on film length at high momentum-flux values) and that the variation in film length generally increases as the momentum-flux ratio decreases (illustrated by the error bars in Fig. 3 which are the standard deviation of the film length). The increase in film length fluctuations at low values of the momentum-flux ratio correspond with observed nonuniformities in the spray.^{9, 10}

Two main categories of nonuniformities were observed in previous work—spray centerline departures (from the centerline of the injector) and pulsing.¹⁰ Three types of centerline departures occurred which can be characterized by the stability of the spray's centerline and the degree of departure—leaning, bouncing and oscillating. Leaning occurs when the centerline of the spray is obviously, usually several degrees, not aligned with the centerline of the injector and the spray maintains that position either indefinitely or for 10's of seconds. When the centerline is obviously misaligned but the spray's center changes over seconds or tenths of seconds then the spray is bouncing. Oscillating sprays exhibit very rapid changes in the spray's centerline location (generally less than 0.1 seconds). The centerline deviation is smaller during oscillating than leaning or bouncing. Pulsing can be divided into axisymmetric and asymmetric pulsing. Axisymmetric pulsing is characterized by an axisymmetric, or nearly so, disturbance on the film surface which, when it exits the injector, results in a distributed pulse of larger droplets, increased droplet density or a sudden increase in spray angle (or some combination thereof). If the disturbance is not fully tangentially distributed then asymmetric pulsing occurs. Figure 4 shows a spray exhibiting a centerline departure behavior while Fig. 5 shows a GCSC injector displaying pulsing behavior. All of these nonuniformities can increase the unsteadiness of the film length.

Pulsing behavior was shown through CFD studies to be the result of two different mechanisms.¹⁰ The separating lip causes a recirculation zone and liquid can be pulled up along the step then forced downstream or the interaction of the gas and liquid can cause the recirculation zones, along with a mass of liquid, to be shed downstream. These results and experimental observations showed that both very thin and very thick liquid post lips should be avoided.¹⁰ Since pulsing occurs due to flow structures at the injector-post lip, it would be expected that pulsing would occur independently of injector cup length and instead depend only on post lip thickness, momentum-flux ratio and swirl velocity.

While investigating the leaning behavior an anomaly at the trailing edge of the injector cup was revealed as shown in Fig. 6a. This anomaly is an area which is devoid (or mostly so) of droplets. This zone either causes the displacement of the gas flow leading to the leaning behavior or is the result of the leaning behavior. Since the only droplet-free gas is that outside of the injector and spray cone, it appears that this gas is being pulled into the injector, possibly due to some flow separation at the exit. This finding is further reinforced by the fact that the spray is not fully attached to the edge of the injector outlet (Fig. 6b). Experiments showed that leaning is related to momentum-flux ratios, not just gas or liquid flow rates.¹⁰ Since leaning is related to this flow separation at the injector exit it is likely that the cup length plays an important role in the leaning and bouncing nonuniformities and demonstrates one reason why the effect of cup length on atomization in GCSC injectors is being investigated.

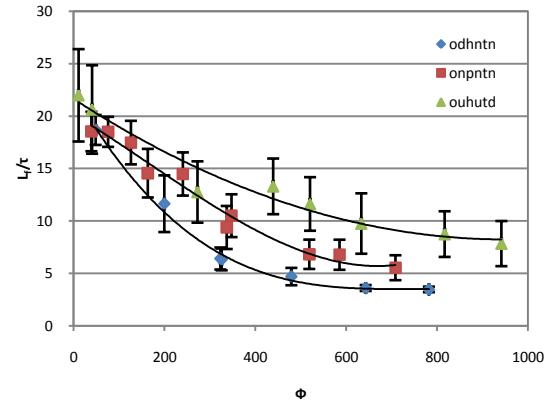


Figure 3. Average film length from both sides of injector cup nondimensionalized by the initial film thickness plotted versus the momentum-flux ratio for three GSCS geometries. Errors bars are ± 1 standard deviation. Shows that the film length scales with the inverse of the momentum-flux ratio and the momentum-flux ratio scaling does not collapse all experimental geometries to a single curve.

^{9, 10}

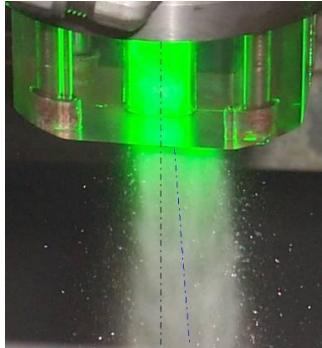


Figure 4. Leaning exists when the spray centerline differs from the injector centerline. This image is annotated with the centerline of the injector (black) and the spray (blue).

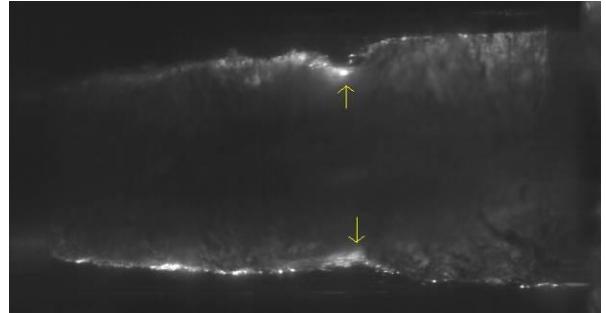


Figure 5. In-cup video frame showing axisymmetric pulsing. Arrows show the approximate center of the waves to aid in their visibility.

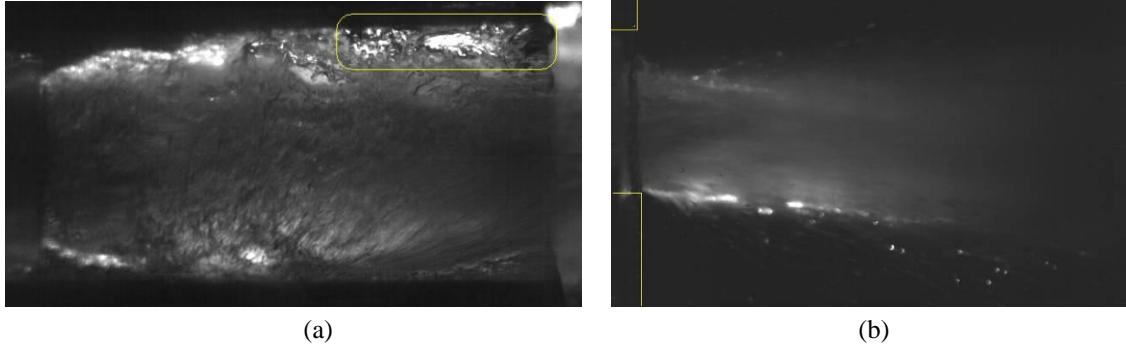


Figure 6. Leaning sprays show a droplet-free zone (a) and are not attached to the injector wall at the exit of the injector (b). In (b) the injector edges are highlighted with yellow lines.

IV. Results and Discussion

In an effort to understand what role, if any, injector cup length plays on setting the film profile and average film length of GCSC injectors, average and instantaneous film profiles were obtained in twelve different injector configurations (six different injector post geometries each with two injector cup lengths). To isolate the effect of injector cup length the same flow conditions were run with the two lengths. An example of this method is given in Fig. 7 images at the same mass flow rates, (and, correspondingly, momentum flux ratio ~ 730) and with the same geometry, ONPDTD, are shown for both the nominal (Fig. 7a) and short (Fig. 7b) lengths. In these images the green dashed lines are the instantaneous film profiles and the red marks are the instantaneous film lengths obtained using the custom Matlab code previously discussed in Section II. From these images it is clear that the film does not smoothly thin out, but thins and bulges as turbulent structures from the gas interact with the surface. The turbulent nature of this atomization process results in the film length varying in time. How much the film length varies from the average value is of critical importance since it sets the injector cup length required to maintain the film inside the cup. Obviously, the average film lengths and their standard deviations are a better metric than the instantaneous film profiles when evaluating the effect of the cup length.

When comparing test cases one must choose which average lengths to compare. Due to the planar imaging method utilized in this work, a film profile is obtained on each side of the injector. At higher momentum-flux ratios the two average film lengths tend to be in close agreement. This is illustrated in Fig. 8 where the average film length normalized by the initial film thickness is plotted for both sides of the image versus the momentum-flux ratio. The

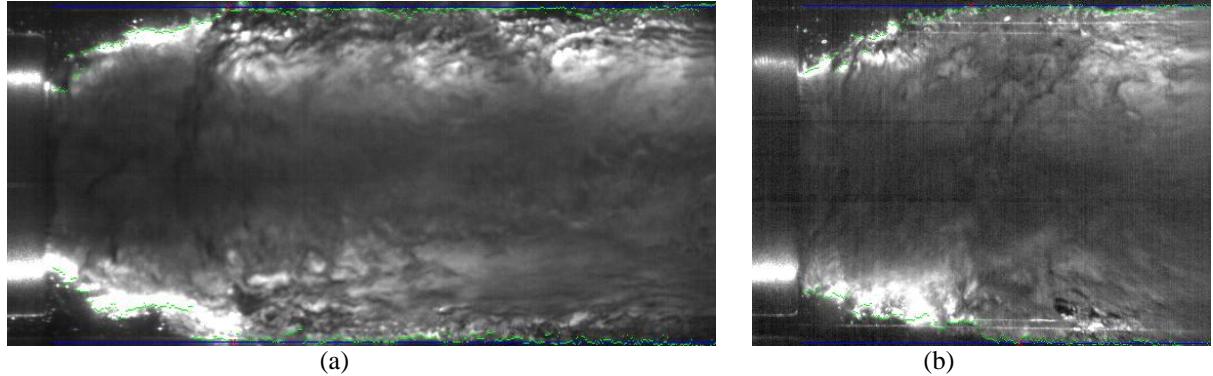


Figure 7. Instantaneous GCSC injector cup images for the ONPDTD geometry with the nominal (a) and the short (b) injector cup lengths. Momentum-flux ratio is ~ 730 . Blue lines are the boundaries of the injector cup, green line are the instantaneous film profile and red x's mark the instantaneous film length.

ONPDTN (Fig. 8a) and ONPNTN (Fig. 8b) geometries are shown. The small differences in average film length between the top and bottom profiles is due to a combination of the difference in lighting between the two sides, the swirling flow, and the uncertainty in the wall location. The swirling flow causes turbulent structures to be illuminated differently since they are moving towards the camera on the top film and away from the camera on the bottom film. The effect of different lighting on the measured film length was investigated in earlier work and found to be less than the standard deviation. Large differences between the top and bottom film lengths can be traced back to nonuniformities in the spray (typically spray centerline departures) which were discussed in Section III. Since these nonuniformities tend to occur at lower momentum-flux ratios so do the large differences in the top and bottom film lengths. This length difference is illustrated in Fig. 8a where the large difference in average film length at $\Phi=250$ and 300 for the nominal cup length correspond to a left-front leaning and a bouncing spray, respectively. This difference in top and bottom film lengths is not seen at these same conditions with the short cup. In an effort to simplify plots the average of the top and bottom film lengths and standard deviations are presented in the remaining plots. Since the same two locations of the film are imaged in the short and nominal cup configurations the average of the two will also correspond as long as any nonuniformities occur in the same direction. It should be noted that average film lengths are plotted only for cases where the film was shorter than the injector cup at least 95% of the time.

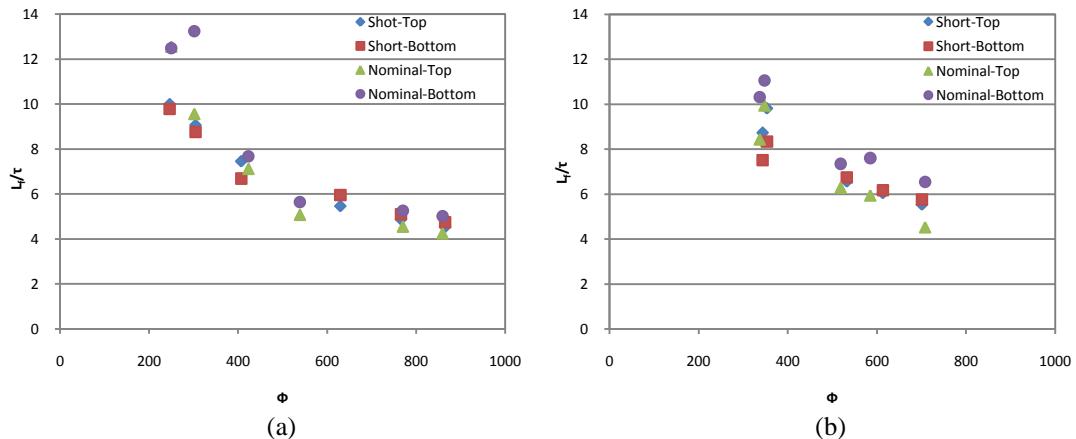


Figure 8. Average film length nondimensionalized by the initial film thickness plotted versus the momentum-flux ratio for ONPDTN (a) and ONPNTN (b) geometries. Nominal and short refer to cup lengths Top refers to the upper film and bottom to the lower film when the injector flow direction is orientated with flow from left to right.

Figure 9 shows the average film lengths for all six injector-post geometries with both the nominal and short injector cup. Error bars in these plots are \pm one standard deviation. For all six injector-post geometries the difference in average film length between the nominal and short injector cases is within the one standard deviation error bars for momentum-flux ratios greater than approximately 400. This result indicates that for films which are well short of the injector length the effect of cup length on the average film length is negligible. Also, the variation in the film length measured by the standard deviation (typically between one and two initial film thicknesses) appears largely unaffected by the cup length under the same conditions. The exception to this is the ONPDTD geometry where the standard deviation of the nominal test conditions is approximately double that of their short counterparts in a few cases. Below momentum-flux ratios of approximately 400 large differences in the film lengths between the nominal and short cup length in some cases can be observed. Also, an increase in the standard deviation for both short and nominal test cases occurs at some conditions. While these momentum-flux ratios are in the regime where the previously mentioned nonuniformities occur, it is impossible to speculate from average film length and their standard deviations how the cup length is altering the film profile and therefore how the film is being atomized. While differences in the average film length occur at individual test conditions, when all average film lengths are plotted on a single graph (Fig. 10) it can be seen that the short and nominal cup average film lengths collapse nicely to a single curve. The large scatter in the film length for the nominal cup length below momentum-flux ratios of approximately 400 corresponds to the observed nonuniformities in the spray. The scatter is much less in the short cup length results since cases with low momentum-flux ratios, where these nonuniformities typically occur, have film profiles longer than the injector cup and are, therefore, not included in Fig. 10. Also, short cases were leaning occurs and one film length is much longer than the other typically results in the long film being longer than the injector; these overlong cases were left off. In the nominal case, however, these films are still completely contained in the cup and are included. Note that Fig. 10 collapses to a single curve and not the previously mentioned family of curves since only a single injector cup radius was tested in this current study.

To further investigate when and how the injector cup length alters the liquid film profile and atomization of GCSC injectors, average film profiles were obtained for all test geometries. Average profiles for the same test conditions but with the short and nominal cup where scaled to the same dimensions and plotted on top of the experimental geometries. Examples of these plots are shown in Fig. 11 where six different test conditions for the ONPNTN injector post configuration have been graphed. These plots were then compared with notes of the spray behavior taken during testing in an effort to find trends in how the cup length altered the film profiles and observed nonuniformities. In all cases (including those shown in Fig. 11) the average film profiles from the nominal and short injectors showed some departure from one other. Sometimes this departure is very minor and only occurs at the end of the injector lip (e.g., Figs. 11e & 11f) while at other times it continued the entire length of the film (e.g., Fig. 11a). Comparing these departures with notes on the observed spray behavior yielded a few observations. Generally, film profiles from the 2 injector lengths were more likely to agree if neither leaned; however, this has a momentum-flux ratio component since high momentum-flux ratio conditions are less likely to lean. Also, no obvious in profile agreement was found between cases where only one cup lean was observed to lean versus when both cup lengths exhibited leaning.

Part of the reason for the lack of trends between spray behavior and film-profile departure may relate to the difficulty in observing some of these spray nonuniformities by eye. In a number of cases leaning and bouncing behavior was observed in the nominal case, but the short spray had a double-cone spray making it difficult to observe nonuniform behavior in the inner cone. Also, in some of these double-cone cases where leaning was not observed recirculation zones were found in the injector cup- an indicator leaning or bouncing is occurring. Note that a double cone can still occur while the film is completely contained in the injector. This situation occurs when the film length is about the same length at the injector cup and the expansion at the end of the injector leads to the breakup of the film. This breakup creates relatively large droplets that are flung to the side instead of following the gas stream thus forming the second cone. This type of breakup leads to a thinning of the film near the injector exit that would not occur if the injector cup length was longer. This thinning can be seen in Figs. 11a and 11b. To better understand the correlation between film profile differences and spray nonuniformities, spray videos and mass distribution profiles are needed.

Comparison of the average-film-length plots showed that, while high momentum-flux ratios produced fairly good agreement between the profiles of the short and nominal injectors, departures still existed at all values. In an attempt to quantify these departures, the difference between the profiles was obtained at 4 downstream locations (2, 5, 10, 15 mm) and plotted against the momentum-flux ratio. In Fig. 12 these differences normalized by the initial film thickness are plotted for the top film profile at the 2 and 15 mm locations. At 2 and 5 mm no correlation of the profile departure with the momentum-flux ratio is evident. However, at 10 and 15 mm there is a general decrease in the departure of the two profiles until a momentum-flux ratio of approximately 400 and then a leveling off above

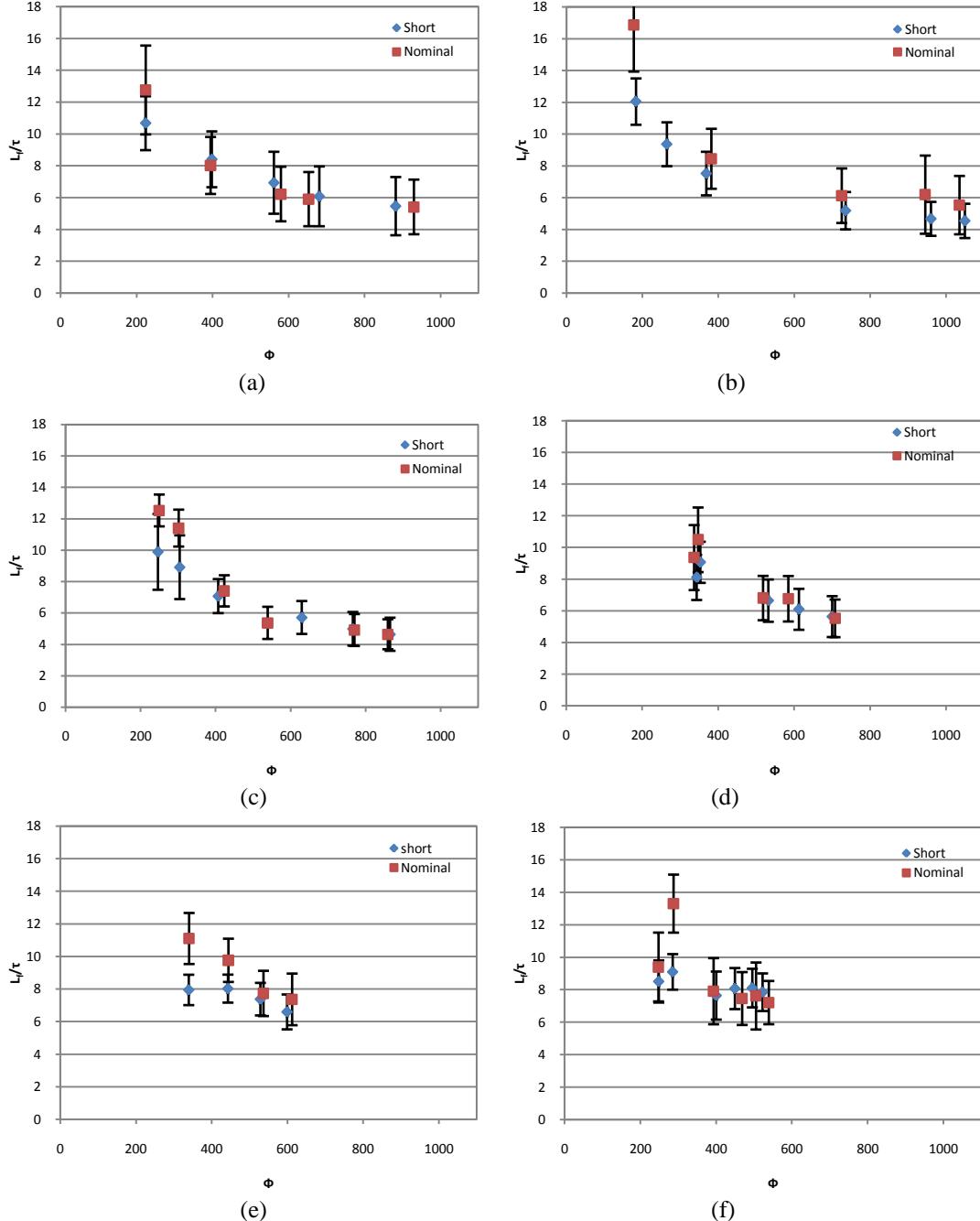


Figure 9. Average film length nondimensionalized by the initial film thickness plotted versus the momentum-flux ratio for the six injector post geometries (ONHNTD (a), ONPDTD (b), ONPDTN (c), ONPNTN (d), ONPNTU (e)). The error bars are \pm one standard deviation of the film length.

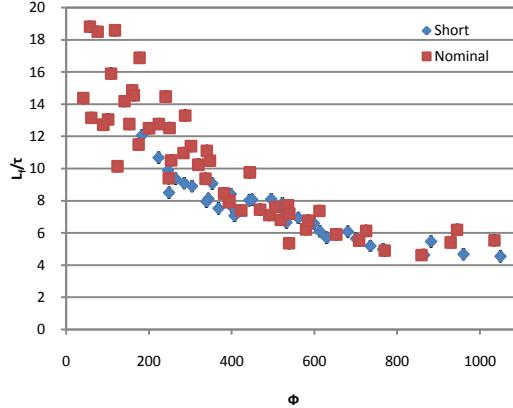


Figure 10. Average film length from both sides of injector cup nondimensionalized by the initial film thickness plotted versus the momentum-flux ratio for all nominal and short injector test cases.

400. This leveling off corresponds with the momentum-flux ratio range where excellent agreement was found between the nominal and short average film lengths. Since this leveling off occurs at a nonzero number it is likely representative of the error in the measurement and scaling of the film profiles. The inability to collapse the departures of the profiles at 2 and 5 mm points to the chaotic nature of the film at that location and possibly a phenomenon or an error that is not yet fully understood.

V. Conclusion

In an effort to obtain design criteria for Gas-Centered Swirl-Coaxial (GCSC) injectors for use in liquid rocket engines the effect of the injector cup length on the wall-bounded-film profile and length was investigated. The film length was used as a segregate for overall injector performance. This study built on earlier work which explored atomization models for GCSC injectors and varied important parameters such as the cup radius, step thickness, gas radius at the end of the sheltered lip and the initial film thickness. In this work experimentally measured profiles were obtained for six different injector post geometries each of which was tested with constant nominal and short injector cup lengths of 35.54 and 19.41 mm, respectively. Results showed that the injector cup length had a negligible effect on the average film length and the standard deviation of the film length above a momentum-flux ratio of approximately 400 for all geometries. This held as long as the injector was longer than the vast majority of the instantaneous film lengths. Below a momentum-flux ratio of 400 differences were observed between some of the nominal and short cup lengths which corresponded with previously observed nonuniformities in the spray. However, when all film lengths from both injector lengths were plotted on a single graph all data points collapsed to a single curve with the short film lengths falling well within the scatter of the nominal cup results. An attempt to correlate deviations in the average film profiles between short and nominal test cases was met with mixed success. In previous work a minimum momentum-flux ratio around 600 was given as a design criterion to avoid nonuniformities in the spray. Given the results of this work this criterion can be left unchanged. The only additional requirement on the injector cup length is that it can contain the longest instantaneous film lengths at all run conditions.

A great deal of future work is planned to finish characterizing GCSC injectors in the cold flow environment. Planned future work includes varying in the swirl component of the liquid sheet through changes in the number of injection holes and total injection area, spray characterization including droplet sizes and velocities, and measurements of sprays exiting to elevated pressure (as would occur in an actual engine). In addition, data from this work continues to be utilized as an anchor for simulation and physics based modeling efforts.

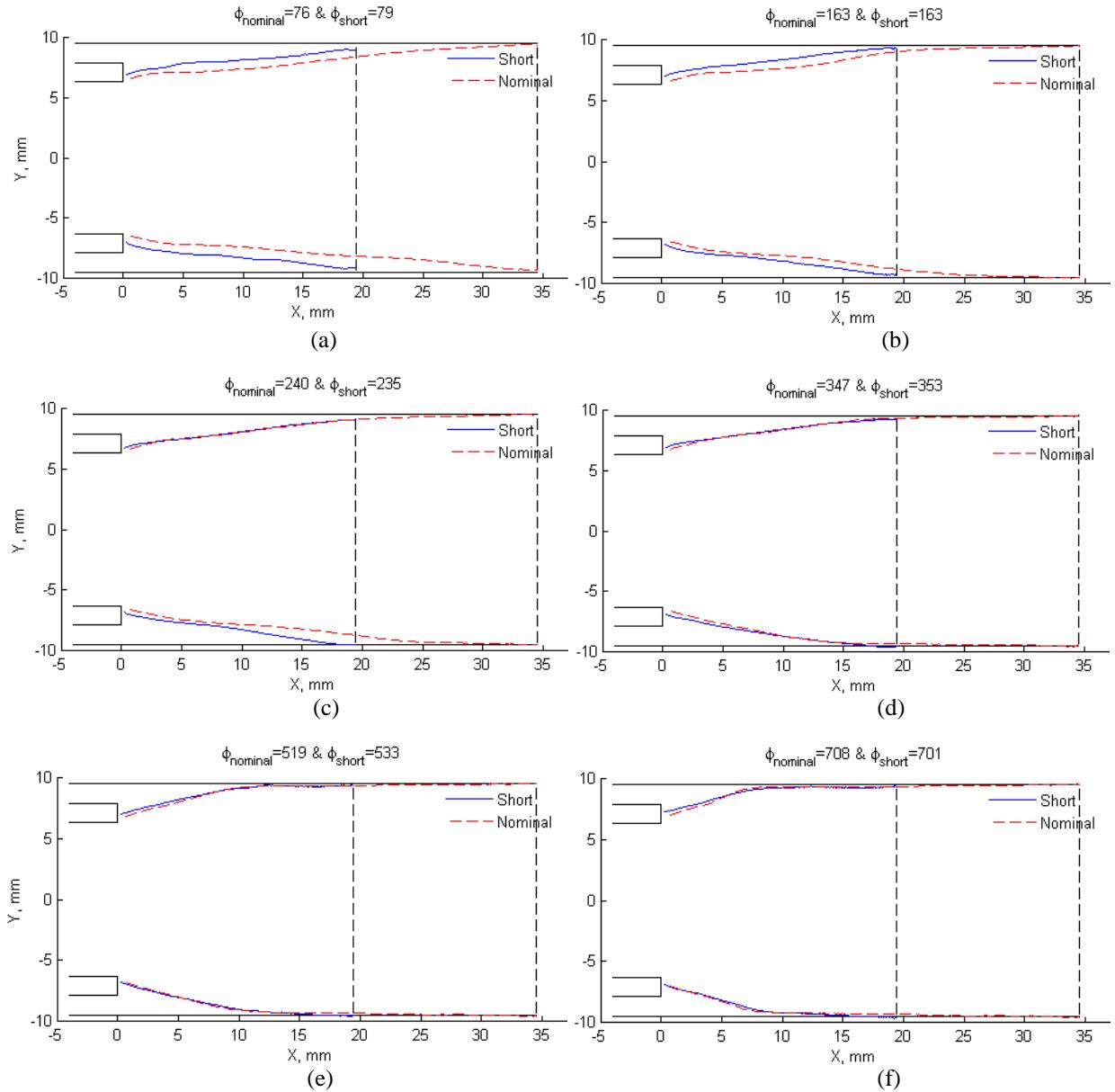


Figure 11. Average film profiles for six test conditions with the ONPNTN injector post geometry. Momentum-flux ratios for both the short and nominal test cases are provided above each plot. The first vertical dashed line represents the end of the short injector configuration and the second dashed line the end of the nominal injector configuration.

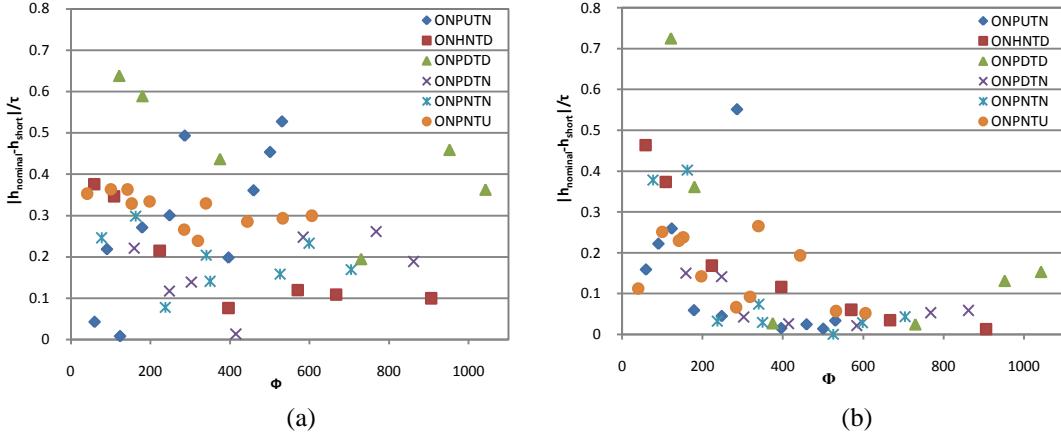


Figure 12. Absolute departure between top film profiles of the nominal and short injectors. Departures in height are normalized by the initial film thickness and plotted against the momentum-flux ratio at downstream locations of 2 mm (a) and 15 mm (b).

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